REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
02/11/01

2. REPORT DATE
Final Technical

3. DATES COVERED *(From - To)*
04/01/99 to 04/09/01

4. TITLE AND SUBTITLE
Vortex packets in turbulence boundary layers with application to high Reynolds number effects, isolated and patterned roughness near wall modeling and strategies for drag reduction

5a. CONTRACT NUMBER
N00014-99-1-0188

5b. GRANT NUMBER
N00014-99-1-0188

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
99 PRO2908-00

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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10. SPONSOR/MONITOR'S ACRONYM(S)
ONR 254

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release

20011106 133

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The scientific goals of this work are to develop a complete physical model of turbulence in wall boundary layers and to develop means of describing and modeling surface roughness effect. We make use of recent developments in our understanding of the mechanistic structure of near-wall turbulence for smooth walls at low Reynolds numbers to understand how large Reynolds number and wall roughness affect turbulence. We build upon experimental and computational evidence from smooth walls to extend the mechanistic picture of turbulence based on a paradigm of *hierarchy of hairpin packets* to high Reynolds number, when roughness effect increases in importance. Both experimental measurements of velocity field in smooth and rough walls and direct numerical simulations of evolution and interaction of hairpin vortices are used.

15. SUBJECT TERMS
wall turbulence, roughness, hairpin packets, log-law

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
			SAR	16	S. Balachandar
					19b. TELEPONE NUMBER *(Include area code)* 217 244-4371

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

Final Report

Contract Information

Contract Number	N00014-99-1-0188
Title of Research	Vortex Packets in Turbulent Boundary layers with Application to High Reynolds Number Effects, Isolated and Patterned Roughness, Near Wall Modeling and Strategies for Drag Reduction
Principal Investigator	R. J. Adrian and S. Balachandar
Organization	Univ. of Illinois, Urbana

Technical Section

Technical Objectives

Long-term, our scientific goals are to 1) to develop a complete physical model of turbulence in wall boundary layers, and 2) develop means of describing and/or modeling fine-scale surface effect in computational models of wall-bounded turbulence that cannot, for practical reasons, fully resolve the fine scales. The medium term goals of this work are to make use of recent developments in our understanding of the mechanistic structure of near-wall turbulence for smooth walls at low Reynolds numbers to understand how large Reynolds number and wall roughness affect turbulence close to marine vessels surface. Much of Navy's interest is in the high Reynolds number regime, related to drag reduction and wake signature control of seagoing vehicles. The specific goal of the work is to build upon experimental and computational evidence from smooth walls (Meinhart & Adrian 1995, Zhou *et al.* 1999, Adrian *et al.* 2000) to extend the mechanistic picture of turbulence based on a paradigm of *hierarchy of hairpin packets* to high Reynolds number. In considering high Reynolds number, one must also consider the effects of roughness, since what appears to be a smooth wall at low Reynolds numbers will begin to directly influence the near wall processes at higher Reynolds numbers. Thus, this work also attempts to understand how roughness affects the structure. This will impact the *technology* of marine vessel design by improving the capability to predict the effects of various types of surface roughness on local drag.

The near-term objectives of this project are to establish the extent to which the hairpin vortex paradigm explains phenomena that are important in the flow over rough surface, and to evaluate the effects of the detailed geometry of roughness elements.

Technical Approach

The rough surface of a marine vessel may look less like a piece of sandpaper, as in the classical sand grain roughness picture of rough walls, and more like a collection of discrete bumps. Thus, one should distinguish between distributed roughness and discrete roughness. We visualize discrete roughness elements generating a series of hairpin vortices. The hairpins grow in size as they travel downstream and their heads moves farther away from the wall. Correspondingly, the disturbance due to a bump begins to look like those found on smooth walls due to the autogeneration mechanism for hairpins. The hairpin packet is also expected to grow in size and provide the environment for the formation of a new hairpin and subsequently the next generation hairpin packet within it. At high Reynolds numbers, as

the older hairpin packets continue to grow-up, this process conceivably continues leading to the formation of a hierarchy of packets. Perry and coworkers (Perry *et al.* 1986) have previously considered a similar hierarchy of hairpins (but not packets) as a model of turbulent wall layer. Convincing experimental evidence for such hierarchy can be Adrian, Meinhart and Tomkins (2000).

One of the most famous empirical 'laws' in turbulence is the logarithmic profile with the associated von Karman constant. The constant applies for a variety of flows - boundary layer, pipe, channel, smooth wall, rough wall- and its value is independent of the Reynolds number. The logarithmic variation is used to set a wall boundary condition in the vast majority of all turbulent CFD solutions of flows involving solid boundaries. The essential features of wall turbulence and the logarithmic law may reside in these packets, including a geometric explanation of the value for Von Karman's constant. The tendency of roughness elements to produce vortices similar to smooth walls may also explain the occurrence of the logarithmic layer in both cases. Thus, one of the foundations of the present technical approach is to compare vortices from roughness elements to those occurring over smooth walls. Companion computations are also performed to determine how interactions of hairpin packets affect drag at the wall, and the formation of a self-similar hierarchy of hairpin packets.

Experimental Results

All PIV measurements in planes parallel to a smooth wall in a boundary layer wind tunnel have been completed in the Ph.D. thesis of C. Tomkins (Tomkins 2001). These include measurements over smooth wall, which serve as a basis for comparison with the discrete wall measurements, and measurements of arrays of discrete elements consisting of hemispheres on the wall. These elements replaced a computer controlled solenoid-actuated piston, which momentarily injected low momentum fluid into the near-wall region of the boundary layer at a point, since the piston was not practical for constructing an array of disturbances. A series of PIV measurements were also performed over arrays of short cylinders mounted perpendicular to the wall. It was found that the cylinders produced closed wake behind them that became smaller in the streamwise direction, whereas the hemispheres produced wake that grew upwards, in the fashion expected for a hairpin packet. Thus two elements having nominally the same drag per element produced quite average flow. Neither produces flows whose mean variations were convincingly logarithmic.

Tomkins' experimental studies also addressed two vexing questions concerning the hairpin vortex paradigm: does the near-wall buffer layer exist more or less independently of the inclined hairpin? And, how do the hairpins grow laterally? If they start at approximately 100 viscous wall units spacing and grow, then there must be a mechanism for making room for the growth. Tomkins has found strong evidence to support a picture in which the packets grow upwards and sideways in a nearly self-similar manner until they interact with neighbors. Then, a merging occurs in which two laterally placed hairpins merge to form a new hairpin twice as wide. The process occurs because adjacent legs of the hairpins have opposing vorticity that allow them to negate each other (see for example PIV fields shown in figures 1 and 2).

Measurements behind individual roughness elements in a fully turbulent layer suggest that element shape has a significant effect on vortex shedding: a hemisphere is observed to create more vortices downstream than a vertical cylinder with the same projected frontal area. However, the turbulence appears to disrupt the periodicity of the shedding process, as periodic shedding is not observed downstream of the elements. The concept that roughness element shape affects vortex shedding and flow behavior well downstream of the element has clear implications for flows over three-dimensional rough surfaces of any type.

The flow over a full array of hemispheres is also investigated. Here PIV measurements are obtained in the streamwise-wall-normal plane over a full period spanwise. The roughness is observed to slightly disrupt the vortex organization observed over the smooth surface, as evidenced by reduced streamwise length scales. However, vortex packets that bear many similarities to the smooth-wall packets do appear over the roughness, suggesting that the mechanisms of packet formation are both robust and universal.

Also, the elements are observed to introduce structure into the layer that adopts the length scale of the roughness. Large elements, for example, are observed to create large vortices, which, in turn, create large intense ejections in the inner layer. The idea that wall-mounted elements may consistently introduce structure into a fully turbulent layer, and that the scale of this structure may be controlled by the element size, has implications for passive control of wall turbulence.

Computational Results

A new direct numerical simulation code gives double the Reynolds number that was previously attained in our simulations of hairpin packet growth (Re_τ=590 vs. 300) At this Reynolds number the complex growth of a packet looks much more like the complex fields that are seen in fully turbulent DNS results for channel flow. The higher Reynolds number allows us to track a packet over twice the age, and hence to observe the clear formation of a hierarchy of packets.

The existence of hairpin vortex packets in Re = 590 in DNS channel flow has been demonstrated, and comparisons of the vortex packet structure with the low *Re* number cases (150, 300) have been made. The evidence supports the conclusion that hairpin vortex packets are universal in wall turbulence at *Re* number in the range of our cases.

Evolution of a single hairpin vortex in a turbulent mean flow at high *Re* case showed that the autogeneration process by which the single strong initial hairpin vortex evolves into a packet of streamwise aligned hairpins to be fundamentally the same as that observed in the previous evolution studies conducted at low *Re* cases of 150 and 300. The resulting hairpin vortex packet structure is similar to Zhou *et al*'s studies. Our study shows that in a long time evolution a slight spanwise disturbance can cause development of an asymmetric hairpin packet with more complicated structure than the symmetric one. This kind of complicated structure is seen very often in a real wall turbulent flow. Both results of symmetric and asymmetric packet evolutions are used for comparisons with the high *Re* case of 590.

The evolution of groups of packets has also been studied to see if the pattern of packets as created by a patterns of discrete surface roughness elements has a significant effect on the surface drag. Since vortex packets inevitably interact with themselves knowledge of the interactions between packets is needed for understanding the instantaneous vortical structure. Since the hairpin packet and its evolution are similar at different *Re* numbers and the computation time for high Re case is about 9 times longer than the *Re* of 300 case (with grids of 4.5 times more and time step of 2 times smaller than the low *Re* case), we have performed the computations of evolution and interactions at low *Re* of 300 first. The evolution study at high *Re* case will be performed later afterward.

Eleven cases of evolution have been studied at low *Re* = 300. See **Table 1**. (The initial structure in each case, except case A, has strength that is four times above the threshold for generating a packet:

a. Case A. A single asymmetric hairpin with strength factor of 1 (below a threshold). The evolution up to $t^+ = 642$ never resulted in a packet.

b. Case **B**. A single asymmetric hairpin evolution up to $t^+ = 528$. The structure of the resulting vortex packet is more complicated than the symmetric case **C**, but very similar to those often seen in a real instantaneous wall turbulent flow.
c. Case **C**. A single symmetric hairpin evolution up to $t^+ = 392$. The evolving packet structure is similar to Zhou et al's results.
d. Case **D**. Two hairpins 104^+ apart in the streamwise direction evolving up to $t^+ = 556$. The two initial structures quickly merge into one and develop at a faster pace into a stronger vortex packet than from a single initial structure.
e. Case **E**. Two hairpins of different ages ($t^+ = 0$ and 12^+ in a single hairpin evolution) 208^+ apart in the streamwise direction evolving up to $t^+ = 356$. The older hairpin catches up very quickly with and annexes the younger, and evolves into a stronger vortex packet.
f. Case **F**. Two hairpins of different ages ($t^+ = 0$ and 12^+ in a single hairpin evolution) 326^+ apart in the streamwise direction evolving up to $t^+ = 404$. The interaction is similar to case **E** with a slower pace.
g. Case **G**. Two hairpins 104^+ apart in the spanwise direction evolving up to $t^+ = 532$. The evolution involves strong interactions of hairpins: vortex pairing, combination, annihilation and generation of new hairpin vortices with the same and also larger spanwise scales. The spanwise interactions of vortices appear to be much stronger than the streamwise interactions.
h. Case **H**. An array of 5 hairpins evolving up to $t^+ = 576$, four of them being located at each corner of a rectangle with one in the middle. The geometry of the rectangle is 120^+ by 104^+ in the streamwise and spanwise directions. The interactions involve both streamwise and spanwise packets they, and result in complicated vortical packet.
i. Case **I**. An array of 15 hairpins evolving up to $t^+ = 536$. Each 3 of them formed a group and was aligned in the streamwise direction with spacing of 120^+. 5 groups subsequently were arranged in the spanwise direction with spacing of 104^+ and with every other group (actually 2 of them) being staggered back one-half spacing in the streamwise direction. This case was intended to simulate the flow above the elements of a rough wall.
j. Case **J**. An array of 21 hairpins evolving up to $t^+ = 316$, each 3 of them formed a group and they were aligned in the streamwise direction with spacing of 120^+. Resulting 7 groups subsequently were arranged in the spanwise direction with spacing of 104^+ and with no staggering in the streamwise direction. This case was also intended to simulate the flow above the elements of a rough wall.
k. Case **K**. Ten hairpins 104^+ apart in the spanwise direction evolving up to $t^+ = 300$. Note, in case **G**, there were only two hairpins aligned in the spanwise direction. Case **K** showed that interactions in pairs.

2. One case of evolution has been studied at $Re = 590$:
   Case **L**. A single symmetric hairpin evolution up to $t^+ = 360$. The basic feature of the evolving vortex packet is similar to low Reynolds number cases (150 and 300) with some minor new features, e.g. the 'tongue' is much longer and active in creating new downstream hairpins.

3. Reynolds stresses and instantaneous mean profiles have been calculated for five cases (**C, D, G, H** and **I**) and the effects of interactions on them have been explored.
   a. The Reynolds stresses were calculated for each evolution time stage in terms of volume average of the lower half channel domain where the evolution of the initial structure took place. The Reynolds stresses for each time stage was normalized with the values at zero time stage, so that the change in each time stage will be easy to visualize.

b. We are more interested in the change of Reynolds stress <uv> as the evolution in time develops.
c. For the evolution of a single initial hairpin-like structure (case **C**) the Reynolds stress increases in time. The increase is obviously caused by the generation of new hairpins that become part of the vortex packet. The new hairpins form a coherent vortex group aligned in the same streamwise direction. Each hairpin not only induces a Q2 event under itself and also enhances the Q2 events under other hairpins. The total effects of enhancement of Q2 events are larger than the sum of themselves.
d. For the interaction of two hairpins in the streamwise direction (case **D**), Reynolds stress decreases a little at first and then goes up at later time.
e. For the interaction of two hairpins in the spanwise direction (case **G**), Reynolds stress increases with time very rapidly at later time due to new generated larger spanwise scale vortices. The result shows that the spanwise interaction is more effective than the streamwise interaction in creating higher Reynolds stress.
f. For the case **H** where exist both streamwise and spanwise interactions, Reynolds stress decreases a little before $t^+ = 200$, and then increases to a level higher than the case **D**, streamwise interaction alone, but lower than the case **G**, only spanwise interaction.
g. For the case **I** where the initial vortices are arranged in an array, Reynolds stress behaves complicated corresponding to the vortex interactions in the evolution.

From our observations the streamwise interaction tends not to make obvious changes in the streamwise scaling, although it induces generation of more hairpin vortices in the packet than the single hairpin evolution. However, the spanwise interaction does make changes in the spanwise scaling. Vortex scale doubling in the spanwise direction is seen very often. During spanwise scale doubling the streamwise momentum jumps upwards, indicating a decrease in the wall shear stress. Thus, patterns of discrete elements that could promote the spanwise interactions may be useful in reducing wall friction.

Lateral interaction between hairpins must be an important ingredient in the spanwise scaling of the hairpin vortices as they grow along the streamwise and wall-normal directions. As the packets expand in the spanwise direction they must ultimately interact by vortex encounters. Encounters also occur due to larger, faster packets running over smaller, slower packets. Some such possible vortex packet encounters as seen in the DNS results are depicted schematically in Figure 3. In lateral encounters, the opposing vorticity in adjacent legs of two hypothetically identical hairpins could annihilate them, resulting in a larger hairpin of the same height, but double the width of the original hairpins. Figure 3(a) shows schematically such a lateral vortex merger resulting in larger hairpins having twice the spanwise spacing of $\lambda_z^+ \cong 100$. Further lateral merging of the larger hairpins can lead to subsequent progressive increase in spanwise scale. We therefore envision the growth of scale in the wall layer to occur both by continuous expansion of the eddies in an individual packet and the merger of eddies in adjacent packets.

Figure 3(a) depicts a scenario where there is perfect symmetry along the spanwise direction, while Figure 3(b) shows a more realistic scenario where perfect spanwise symmetry is not present. Vortex reconnection and merger still apply, and spanwise growth of the hairpin can be anticipated. Thus, Figure 3(b) considers a taller upstream packet that travels faster and catches up with the shorter downstream packet. Vortex reconnection occurs at the point of intersection of the vortex cores, and the exact location depends upon the geometry and size of each hairpin. Observations of fully turbulent DNS results suggest that other scenarios of spanwise growth can also be conjectured, such as that shown in Figure 3(c). In the early stages of their development the hairpins vortices are observed to have a Ω-shaped head (Zhou *et al.* 1999). Consequently, the first intersection of two hairpins may occur at the outermost sections of the Ω.

A spanwise vortex merger of this nature can be seen in Figure 4, wherein an end-view of two merging vortices from a DNS is shown.

Such vortex rearrangements have a strong influence on near-wall statistics. For example, in Figure 4 as a result of the vortex merger, the back-induction of the hairpin is reduced substantially, leading to a sudden increase in the kinetic energy of the streamwise velocity, which is shown in Figure 5. The effect is to increase drag. Thus, the manner in which the interactions occur is important. As was shown earlier, there is also experimental evidence to support the hypothesis that hairpin vortex packets grow by lateral merger (Tomkins 2001).

Direct numerical simulations of multiple hairpin packets interacting demonstrate several possible consequences for the evolution of the packets. Two such scenarios are shown in Figure 6. In Figure 6(a) and 6(b) the perspective and side views of a complex vortex structure is shown. This structure evolved from an initial condition consisting on five hairpins, four of which were placed at the corners of a rectangle, while the last one placed at the center of the rectangle. The hairpin vortices were allowed to evolve and interact in a background turbulent channel flow of $Re_{\tau}=300$. The vortices evolve and interact in a complex manner and the resulting vortex structure after some evolution is shown in the figure. Evidence of five original hairpin vortices forming a rectangular pattern appears to have been forgotten, indicating considerable spanwise interaction and growth.

Figure 6(c) shows the vortex structure resulting from the interaction of ten initial hairpin vortices placed side-by-side along the spanwise direction in a turbulent channel flow of $Re_{\tau}=300$. The figure shows the status of the vortex structure after evolution for a short duration. While the ten vortices are clearly visible at the upstream location, the downstream development is influenced by spanwise interaction with the ten hairpins forming five groups after spanwise pairing.

Impact/Navy relevance

The results of this study could improve design of naval vessels, shorten the design process by permitting more confident reliance on CFD results, and lead to new ideas about drag reducing surfaces.

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Table 1. Arrangement of initial structures for different cases in the direct numerical simulations of vortex interactions in the wall layer:

Case	*Re*	**Configuratio n**	Δx^+	Δz^+	T^+	**Symmetry**	a	y^+	**age**$^+$
A	300	>			642	Asymmetric	1	50	0
B	300	>			528	Asymmetric	4	20	0
C	300	>			392	Symmetric	4	20	0
D	300	> >	104		556	Symmetric	4	20	0
E	300	⊃ >	208		356	Symmetric	4	20	0, 12
F	300	⊃ >	306		404	Symmetric	4	20	0, 12
G	300	> >		104	532	Symmetric	4	20	0
H	300	> > > > >	120	104	576	Symmetric	4	20	0
I	300	> > > > > > > > > > > > > > >	120	104	536	Symmetric	4	20	0
J	300	> >	120	104	316	Symmetric	4	20	0
K	300	> > > > > > > > > >		104	300	Symmetric	4	20	0
L	590	>			360	Symmetric	4	20	0

Note: Δx and Δz are separations of initial hairpin-like structures in the streamwise and spanwise directions. T^+ is the total evolution time. Symbol ⊃ represents the initial hairpin with older age than the younger one >. a is the strength factor. The column y^+ indicates the locations of the conditional event Q2. The column age$^+$ indicates the age of the initial structure in t^+ units.

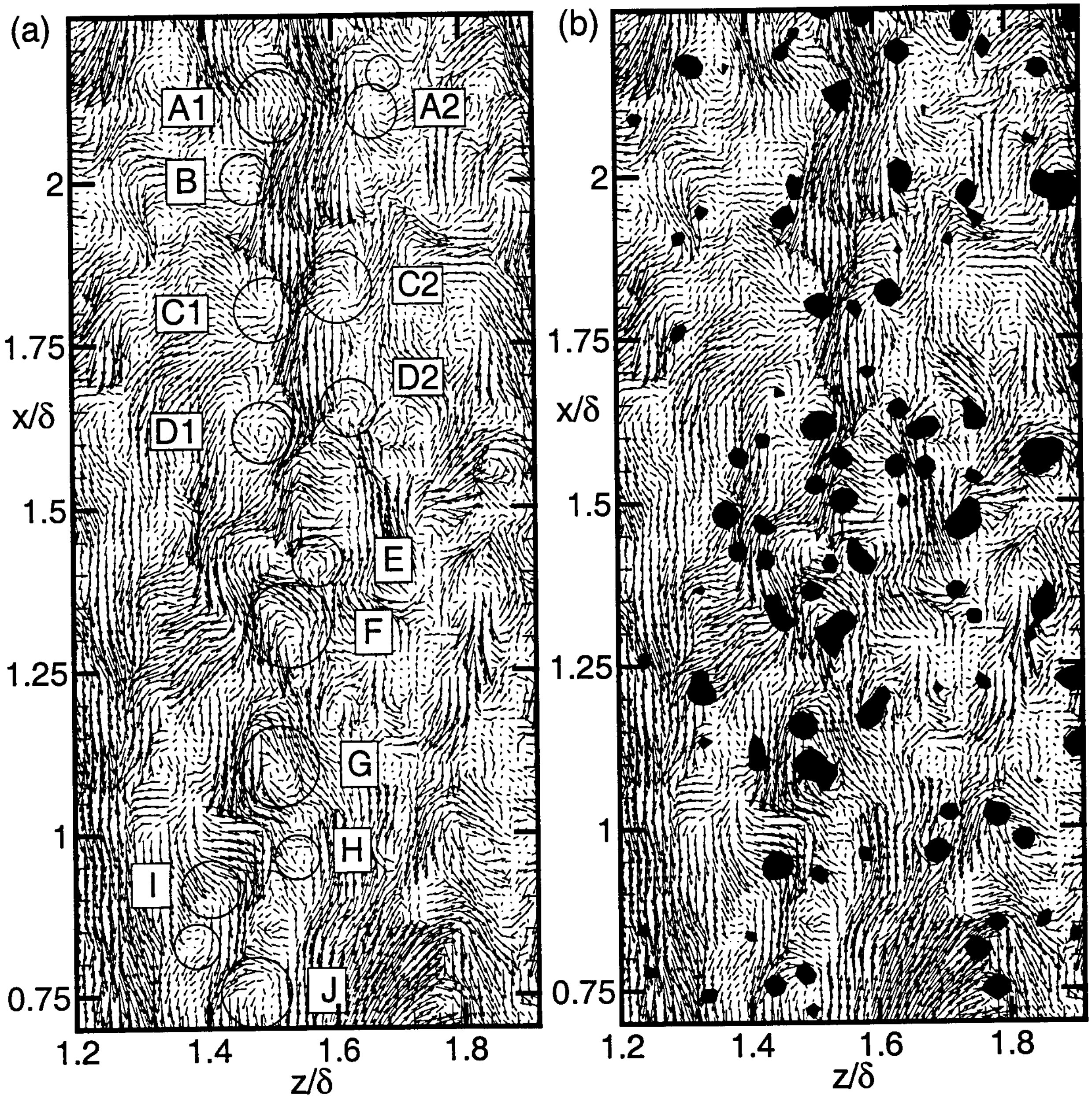


Figure 1. Example of a vortex packet at $y^+ = 100$ in a $Re_\theta = 7705$ layer. Flow is from bottom to top. (a) Velocity vectors reveal an elongated low-speed region to be a concatenation of one and two-legged hairpin vortex signatures; (b) Velocity vectors and contours of swirling strength multiplied by the sign of vorticity. Swirling strength confirms the presence of vortices at regions of rotation identified in (a), and reveals additional structure associated with the sinuous low-speed streak.

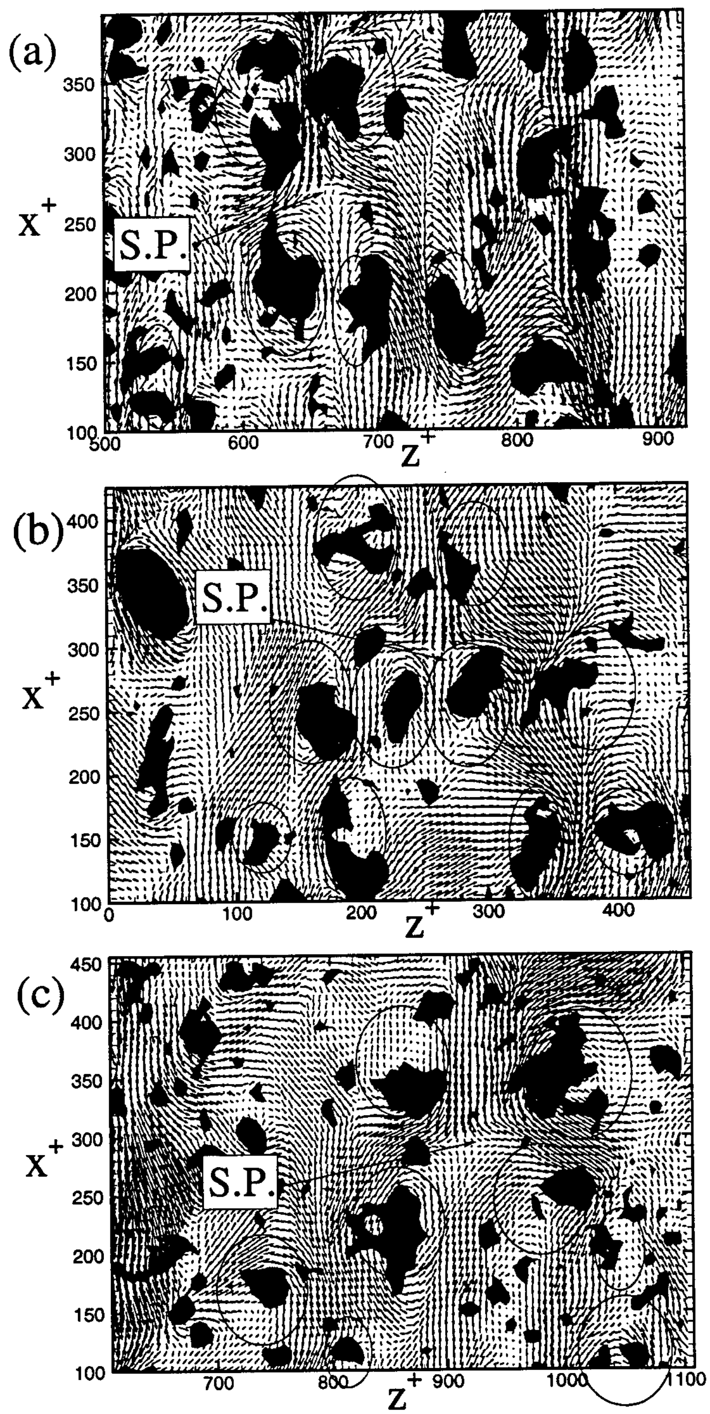


Figure 2. Evidence for scale growth via vortex leg annihilation and packet merging. Instantaneous vector fields are shown with contours of swirling strength multiplied by the sign of vorticity at $Re_\theta = 1015$. The plots reveal the "signature" of merging vortex packets: coalescing low-speed regions bordered by vortices upstream and downstream of the merge location. A stagnation point ("S.P.") appears where the streaks combine. (a) $y^+ = 21$; (b) $y^+ = 46$; (c) $y^+ = 92$.

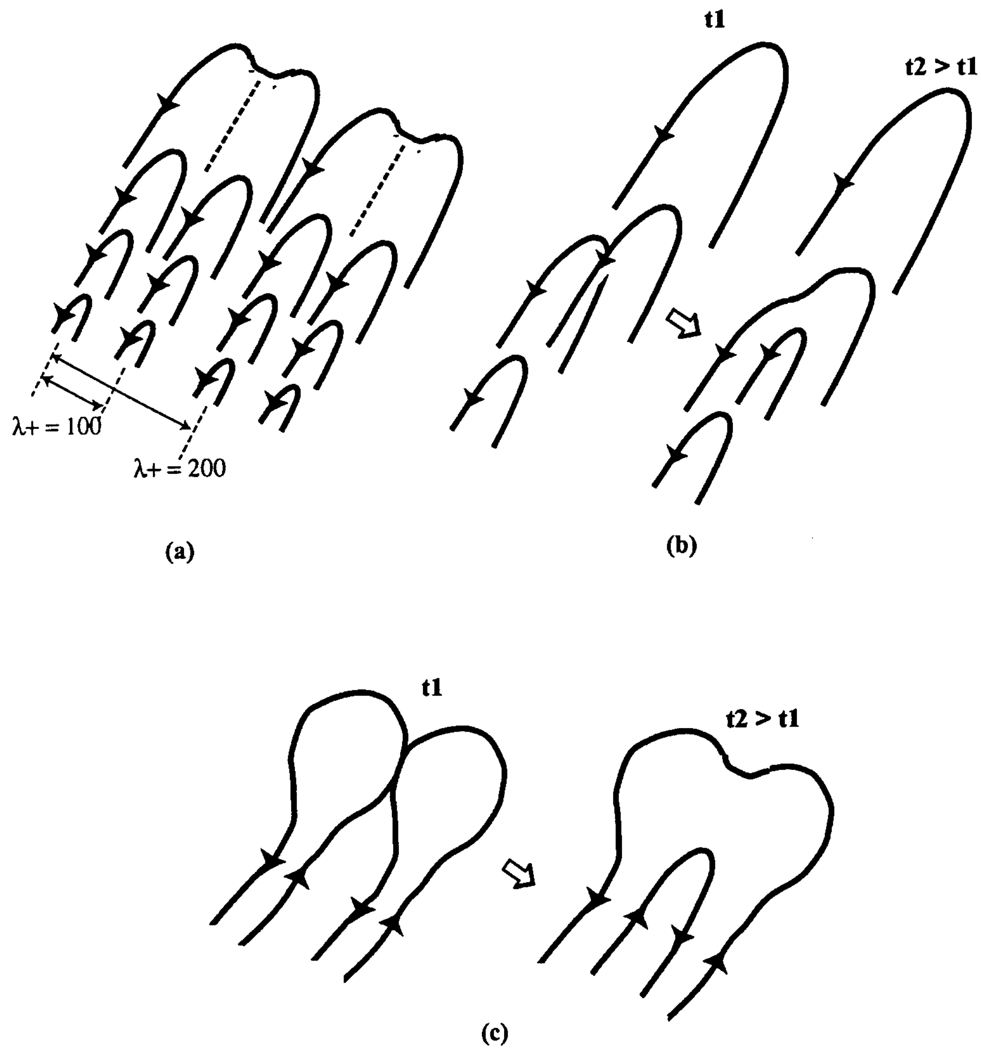


Figure. 3. Spanwise growth by hairpin vortex pairing. (a) Two similar hairpins pairing symmetrically produce a new hairpin whose spanwise width is approximately twice the original width; (b) a faster moving upstream hairpin encounters an offset slower moving hairpin. The vortex cut and reconnection leads to a larger hairpin, similar to case (a) and a smaller hairpin having the same circulation; (c) Two similar, symmetrically positioned omega-shaped vortices connect to form a larger hairpin plus a smaller hairpin having opposite circulation.

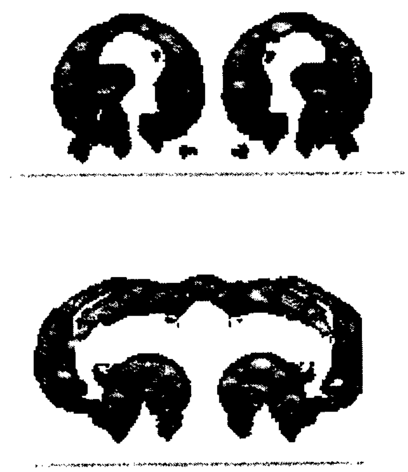


Figure 4. A doublewide hairpin is formed due to lateral encounter of two hairpins. The adjacent legs of two hairpins are annihilated by the opposite vorticity.

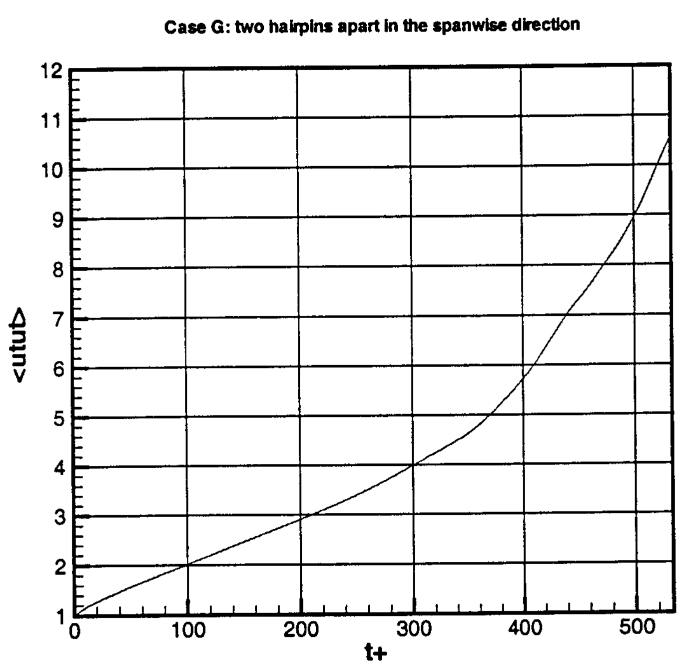
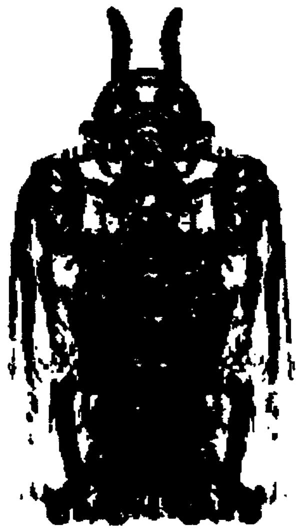
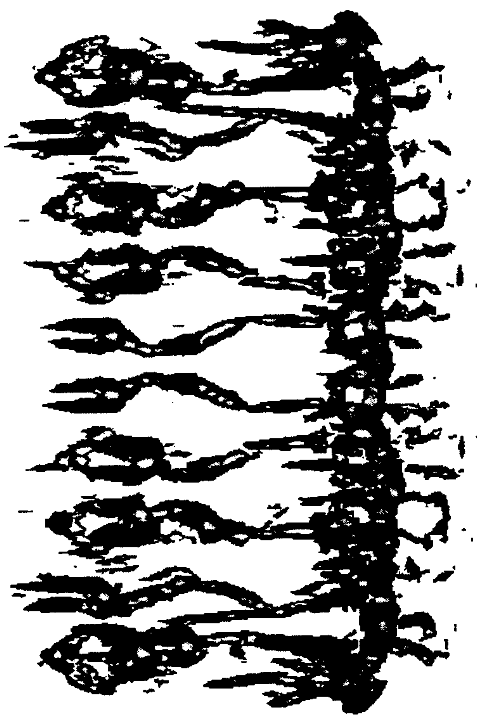


Figure 5. After the lateral encounter of two hairpins the kinetic energy of the streamwise velocity increases more rapidly as a result of a reduction of back-induction by the hairpins.



(a)

(b)



(c)

Figure 6. Interactions of multiple hairpin packets in a mean turbulent flow at $Re_\tau = 300$. (a) and (b) are the perspective and side views of the vortical structure resulting from interactions of five hairpins, four of them are located at each corner of a rectangle and one in the center of it. (c) is the top view of ten interacting hairpins aligned in the lateral direction. After pairing the ten hairpins form five groups, each of them developed from spanwise interaction.

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Presentations

Approximately 10

Books

None

Patents

None

Honors and Awards

Nusselt- Reynolds Prize

Number of students supported by ONR Grant

1 doctoral (C. Tomkins)

1 post doctoral (Z.C. Liu)

0 females

0 under-represented ethnic groups

Grants, contracts and gifts received for research -last 3 years

Year	Brief Title	Source	Amount	#of PIs
12/95-12/00	Structure of Turbulent Convection	NSF-ATM	$865,579	1
2/99	Facility for Integrated Experimental and Computational Research	AFOSR & UIUC	$510,000	2
6/97-6/00	Large Eddy simulation	NSF-CTS	$528,000	3
6/97-6/02	Center for Simulation of Advanced Rockets	DOE	$20,000,000	~30
1/99-1/01	Turbulent Boundary Layers on Rough surfaces	ONR	$270,000	2
8/00-8/03	Integrated Experimental and Computational Multi-zonal Approach	NSF-CTS	$360,000	2